Frequency Scanning Interferometry for CLIC component fiducialisation

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PACMAN Project
Particle Accelerator Components Metrology & Alignment to the Nanometre Scale

- Marie Curie Initial Training Network
- Funded by European Commission & CLIC
- Hosted by CERN
- 10 PhD students

Four Work Packages

WP1: Metrology & Alignment

WP2: Magnetic Measurements

WP3: Precision Mechanics & Nano-positioning

WP4: Microwave Technology

Academic & Industrial Partners

ETH Zürich
Cranfield University
Metrology
ETALON
SIGMA PHI
IFIC
TUDelft
TNO
DMP
Symme
PACMAN Alignment Bench

Goal: To integrate a number of pre-alignment steps in a single test stand

- Seismic sensor
- BPM
- Quadrupole
- Nano-Positioning system
- XY displacement stages
- Fiducial points
- Ø 100 μm CuBe wire
- CMM granite
Background & Objective

- **Requirement:** Fiducialisation of CLIC MBQs
- **Uncertainty Budget:** 10 $\mu$m (1 $\sigma$)
- **Option:** Leitz Infinity ($E_{L,MPE}$: 0.3 $\mu$m + 1ppm)
- **Limitations:** Measurement volume + NOT portable

Goal

Develop & validate an FSI based coordinate measurement system that is:

- Accurate & Precise (<10 $\mu$m uncertainty)
- Portable
- Can handle larger volumes (>2 m length)
FSI: Basic Introduction

Frequency Scanning Interferometry (FSI)

- Absolute distance
- Fringes due to scanning laser
- Unknown length inferred from known reference length

\[
\frac{\Delta \text{Phase}_M}{\Delta \text{Phase}_R} = \frac{L_M}{L_R}
\]

Reference length \( L_R \)
Measurement length \( L_M \)
Frequency Scanning Laser
Absolute Multiline Technology

- Absolute distance measurement (FSI)
- 0.5 ppm (2 σ) Measurement Uncertainty
- 8 simultaneous measurements
- Scalable to 100 measurement lines

@ www.etalon-ag.com
Multilateration

- Coordinate determination using distances only
- Requires distances in different directions from same point
- Uncertainty of coordinates depends on that of **distances** and **geometry** of network
- Compensation for systematic errors is possible
- Coordinates & their uncertainties are the output of least squares computation

**Basic mathematical model**

\[ D + v = \sqrt{(X_S - X_T)^2 + (Y_S - Y_T)^2 + (Z_S - Z_T)^2} \]

Measurement station 
\((X_S, Y_S, Z_S)\)

Distance, \(D\)

Target 
\((X_T, Y_T, Z_T)\)
Absolute Multiline Technology

- Distance between optical fibre tip and retroreflector

- Can’t measure distances in different directions from same point.

- This is required for multilateration
Localization of FSI Optical Fibre Tip

Reference Sphere

- Localization of fibre tip w.r.t centre of sphere
- Ceramic: Can be measured by **QDaedalus**¹ & CMM
- Alumina ceramic: Lower CTE (8.1\( \cdot 10^{-6} \text{K}^{-1} \))
- Diameter: 38.1 mm ± 0.5 µm
- Sphericity: 0.5 µm

¹See presentation by Vasileios Vlachakis: Friday @ 9:15
Kinematic Mount

- 3 ceramic spheres for repeatable repositioning of reference sphere
- Distances in different directions from same point (centre of sphere)
- +/- 44° vertical angle & 360° horizontal angle
- For reference sphere and 1.5 inch diameter retroreflectors
Offset along the beam introduces a constant systematic offset
Can be easily calibrated by a number of techniques

**Calibration of offset along the beam line**

$$D_{1_{meas}} = D_{1_{true}} + X$$

$$D_{2_{meas}} = D_{2_{true}} + X$$

$$D_{3_{meas}} = D_{3_{true}} + X$$

$$D_{3_{true}} = D_{1_{true}} + D_{2_{true}}$$

$$X = D_{1_{meas}} + D_{2_{meas}} - D_{3_{meas}}$$
Reference Sphere – Error Sources

Geometrical Error Sources - Cosine error

- Due to Offset perpendicular to beam line
- Assumption: Beam perfectly aligned to centre of retroreflector

\[ E_y = \sqrt{D_{\text{measured}}^2 + y^2} - D_{\text{measured}} \]
Reference Sphere – Error Sources

Geometrical Error Sources - Sine error

\[ \delta y \approx y \sin \psi \]

\[ \sin \psi = \left( \frac{l}{D_{\text{true}}} \right) \]

\[ \delta y \approx y \left( \frac{l}{D_{\text{true}}} \right) \]
Geometrical Error Sources - Sine error

- Due to Offset perpendicular to beam line
- And lateral misalignment of beam on retroreflector
Combined Uncertainty

Uncertainty in presence to a 1 mm perpendicular offset and a 1.5 mm pointing offset
Reference Sphere - Repeatability

☐ 36 repeat measurements  
☐ Good and Poor alignment  
☐ Shorter and longer distance

Measurement setup

<table>
<thead>
<tr>
<th>Pointing Accuracy</th>
<th>Distance [mm]</th>
<th>Std [µm]</th>
<th>Range [µm]</th>
<th>Distance [mm]</th>
<th>Std [µm]</th>
<th>Range [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>311</td>
<td>2.9</td>
<td>9.8</td>
<td>994</td>
<td>1.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Good</td>
<td>311</td>
<td>0.8</td>
<td>2.9</td>
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<td>0.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Retroreflector Study

- Large acceptance angle targets yield more precise networks
- The acceptance angle of commercial corner cubes is ± 30°
- N=2 glass spheres can be used as retroreflectors
- N=2 glass spheres have an almost unlimited acceptance angle
- Absolute Multiline can measure at distances of up to 4.5 m
- 170 in Observations in total
- 20 Interstation Observations
- 12 Stations, 19 fiducials
- 93 unknowns (X, Y, Z) + 1 reflector offset
Simulation Results

Based on 10 μm a priori distance standard deviation
Next Steps

- Realise high accuracy multilateration – We have all test bench components.

- Carry out comparison tests to validate solution

- Explore motorization possibilities – will speed up data collection, reduce impact of sine error with accurate pointing
Thank You for Your Attention